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ABSTRACT

The experience and advancement of structural dynamics testing for space system applications at the Langley Research Center of the National Aeronautics and Space Administration (NASA) over the past four decades is reviewed. This experience began in the 1960's with the development of a technology base using a variety of physical models to explore dynamic phenomena and to develop reliable analytical modeling capability for space systems. It continued through the 1970's and 80's with the development of rapid, computer-aided test techniques, the testing of low-natural-frequency, gravity-sensitive systems, the testing of integrated structures with active flexible motion control, and orbital flight measurements. It extended into the 1990's where advanced computerized system identification methods were developed for estimating the dynamic states of complex, lightweight, flexible aerospace systems. The scope of discussion in this paper includes ground and flight tests and summarizes lessons learned in both successes and failures.

INTRODUCTION

Structural dynamics testing over the history of the NASA Langley Research Center (LaRC) has been conducted for four primary reasons:

(1) To obtain data to support the improvement of mathematical models of physical systems
(2) To investigate and quantify poorly understood physical phenomena via empirical data
(3) To develop test methods in the pursuit of better information and faster turnaround
(4) To support multidisciplinary systems technology for the control of flexible structures

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Prior to the advent of the space era, the aerodynamic flutter of aircraft wings was a major focus of Langley's structural dynamics research. The technology for using scaled rigid-body models for aerodynamic tests in wind tunnels was extended to include dynamically scaled models of flexible wings and complete aircraft in order to enable simulation of coupled structures and aerodynamics phenomena in practically sized wind tunnels. Building on this background for the space era, dynamic testing to support the understanding and mathematical modeling of the dynamics of space systems followed and became a major technology focus at an ever-increasing complexity of system flexibility, number of components, and detail. The technology for dynamically scaled models was extended to apply to a large variety of aerospace systems including launch vehicles, spacecraft, and early designs for the space station. The work presented here expands on Ref. 1 by including test methodologies and lessons learned. To present events in a chronological order, dates when reports were published are used in most cases as opposed to start date of the activity. Because of the nature and variety of activities reported, at times the discussion may seem disjointed but our goal was to capture work that in some way advanced the state of knowledge at the time.

SCALE MODEL TESTING

Nimbus spacecraft (1964)- This spacecraft, shown in Fig. 1, was one of the earliest examples of the use of scale models for spacecraft dynamics research at Langley. Two different simplified dynamic models, one at 1/5-scale and the other at 1/2-scale, were used in an experimental investigation of the effectiveness of various types of damping treatment in reducing the dynamic response of the spacecraft to vibratory inputs experienced during the launch and boost phases of flight (ref. 2). Tests were conducted using two shakers and crystal accelerometers. Voltages recorded from RMS voltmeters were used to compute amplitudes and frequency counters were used to determine resonant frequencies. Damping estimates were obtained by shutting down the shaker input and plotting free decay data on a log paper to compute the logarithmic decrement. Isolation mounts were shown to be more effective than damping treatment in reducing structural amplification of responses due to solar panel motion of the panels alone at the expense of large motions. Finite difference based models of the ½ scale model showed the 1st ten modes of the solar panel agreed well with tests. Also, the ½ scale model test results agreed with full-scale test results for frequencies up to 35 cps.

Lunar lander scale models (1964)- Langley executed an extensive experimental and analytical program aimed at studying the dynamics problems associated with landing a manned vehicle on the lunar surface. Two of the models used in these studies are shown Fig.1. Both models were rigid-body motion models and had collapsible shock struts in the legs to absorb the impact loads. The model was suspended from cables and swung onto an inclined surface. Instrumentation consisted of strain gage accelerometers located to measure the CG impact and longitudinal accelerations, angular acceleration measured by combining two linear accelerometers, landing gear stroke by measuring amount of crushing after impact, and a motion picture recording at 24 and 64 frames/sec for visual attitude determination on impact. Data were recorded using recording galvanometers with a 24 cps and 120 cps bandwidth. The first model was used in a program (refs. 3-4) to develop and evaluate a technique for conducting full-scale landing-impact tests at simulated lunar gravity. Results showed that 95 percent of the landing gear strokes measured for the full-scale test were within 10% of those predicted by the 1/6 scale model. The other model (ref. 5) was used to obtain experimental data to be used to validate analyses then under development for predicting the dynamic response of a lunar landing vehicle during landing impact. These studies showed that for a four-legged vehicle using a 1-2-1 leg sequence on landing can be less stable than a 2-2 sequence.

3/8 scale version early Viking lander (1973)- Studies similar to those done for the lunar lander were conducted in support of the Viking Lander, reported in reference 6. In this case a computer simulation program, developed by McDonnel Douglas, was experimentally validated. Landing was simulated using a drop pendulum with the model released from a predetermined pull-back height to produce the desired horizontal speed at the lowest point of the pendulum swing. Data from piezo-resistive accelerometers, strain gages, and linear potentiometers for stroke measurements were recorded using frequency-modulated magnetic tapes. Results showing good correlation between acceleration, stroke, and vehicle motion provided confidence in computer programs to predict critical response parameters during landing.

Saturn I 1/5-scale replica model (1962)- The idea of utilizing dynamically-scaled models to obtain the vibration data which is necessary for designing complex launch vehicles and their control systems was conceived at Langley and first applied to the Saturn I. A 1/5-scale replica model of the Saturn I vehicle was constructed and its vibration characteristics investigated to establish the feasibility of obtaining the required experimental vibration data with the use of dynamic models, as well as to study the lateral bending vibrations of a clustered-tank configuration launch vehicle. The model, suspended in the test stand during the ground vibration survey, is shown in Fig. 2. The model was designed using replica scaling techniques to duplicate as nearly as possible the geometry of the full-scale structure (including construction methods) and used the same materials. The model was tested on a two-cable suspension system which was designed to study its free-free lateral vibration characteristics (ref. 7), as well as on an eight-cable suspension system (ref. 8) which was designed to simulate the suspension used in the ground vibration survey of a full-scale Saturn I. Fifteen stations of accelerometers were placed along the longitudinal direction to measure bending vibration of the vehicle. Strain gages were used to measure interface forces of the simulated outer LOX tanks. A single shaker was used to excite the model with a frequency sweep from 5 to 90 cps at a constant force level. While dwelling at resonant frequencies, node lines were determined using a movable accelerometer. Data was recorded on an oscillograph, and damping was estimated from a straight line fit through free decay data plotted on semilog paper. Results showed that a suspension system with 2 cables as opposed to 8 (used by MSFC in the full-scale tests) resulted in the smallest effect on frequency and therefore was closest to a free-free test condition. The model and full-scale results are compared in reference 9, where agreement within 6% was reported for the 1st bending mode whereas the first three cluster tanks modes were under-predicted by 10%. Damping factors for full-scale and 1/5 scale were within the same order of magnitude. Results from a torsional vibration survey are reported in reference 10. First torsion and a variety of booster modes were the only modes observed in the 20 to 70 cps frequency range. Changes in booster fuel levels from full to empty resulted in an increase in the 1st torsion frequency by 53%. First torsion and 1st booster cluster modes showed fairly good agreement with full-scale results. The results of the studies conducted on the Saturn I confirmed the premise that the dynamic characteristics of large, complex launch vehicles could be determined accurately from ground vibration tests of properly scaled models.

Titan III 1/5 replica model (1965)- The success of the Saturn I model program prompted the Martin Company to take what was at that time a bold step and opt for using a scale model in lieu of the full-scale vehicle in the ground vibration test which was to be conducted under the Titan III development program to verify the analytical methods being used in its design (ref. 11). To this end, a 1/5-scale replica model of the Titan III was designed and built by Martin with the aim of representing the full-scale vehicle accurately in the frequency range of the lowest three or four longitudinal and lateral vibration modes. Ground vibration tests were performed at Langley on the Titan III in both the III-A (ref. 12) and III-C (ref. 13) configurations. The Titan III-C scale model is shown in Fig. 2. Ground vibration tests at Langley were conducted using similar instrumentation to that used in the Saturn test program. Magnitude information from signals was determined using RMS voltmeters and frequency information was obtained using frequency counters. Phase information was determined from Lissajous plots of output signals and the reference input. This work reports early use of finite elements to create a two-dimensional analytical model of the system, the Raleigh-Ritz method to compute mass and stiffness matrices, and the Matrix Holzer technique to create three-dimensional analytical model. From a testing viewpoint, this was perhaps one of the most advanced tests conducted at the time using 8 matched electromagnetic shakers to excite the structure at various points and a control panel with dual beam oscilloscopes to monitor shaker signals during a sine dwell. Also significant was the explicit use of orthogonality of test and analysis modes as a means to compare structural modes. Only two structural longitudinal modes were discovered in the 10 to 100 cps range for all propellant conditions. It was concluded that coupling between pitch-torsion and yaw-longitudinal did not need to be included in the three-body analysis for modes less than 30 cps.

Saturn V 1/10- scale replica model (1967)- The 1/10-scale model (ref. 14) was intended to be a near replication of the primary structure of the Saturn V. To this end, the model had all the main load-carrying structure of the booster stages represented by essentially replica reproduction of the full-scale structure. However, at one-tenth scale, it was necessary to elastically simulate some upper stage structure and joints. The model shown in Fig. 2 was supported by cables in the test stand in a manner which simulated free-free boundary conditions for the study of either longitudinal vibrations (ref. 15) or lateral bending vibrations (ref. 16). Vibration testing of the 1/10 scale model at Langley was conducted using the same established sine dwell techniques with manual observations of magnitude and frequency information. It was concluded that analysis in which the stiffness coefficients reflected orthotropic membrane properties yielded significantly better results than isotropic analysis for modes involving liquid-tank interactions. Lumped mass models of the tanks and fuel predicted the tank bulging mode very well after refinement of the analytical model using static test data. The model later proved to be of considerable value as a troubleshooting tool when anomalous behavior resulting from the longitudinal oscillations associated with structure-propulsion system coupling (pogo) occurred in an early (unmanned) flight (ref. 17) which resulted in failure of the spacecraft lunar module adapter. Government and industry participated in several studies to gain an understanding of this problem, with Langley using the scale model to study component mode synthesis techniques to determine the behavior of the lunar module, lunar adapter, and module adapter.

1/40 scale Saturn V model (1968)- This model was intended to be employed primarily in an investigation to determine the coupled vibration characteristics of the combined Saturn V—launch platform—umbilical tower configuration which comprised the mobile launcher complex (ref. 18). Because of its small size, replica scaling was not possible and the model was designed to maintain equivalent stiffness and mass distributions to ensure dynamic similarity with the full-scale vehicle. The model of the Saturn V was basically a machined tube, with magnesium as the primary material, having simulated joints at the proper locations. The scale model hardware included a fuel slosh simulation consisting of spring and mass assemblies, which could be located at various positions in the first stage of the model. The launch platform and umbilical tower were also 1/40-scale, dynamically similar representations of the full-scale structures. A photograph of the suspended from cables is shown in the photograph. Test results are reported in reference 18, while analyses and comparisons with test are described in reference 19. One major finding from this study was the considerable coupling between the launch vehicle and the umbilical tower at higher frequencies (> 60 cps), but at low frequencies little coupling existed even though both the scaled tower and scaled vehicle had their 1st cantilever mode below 60 cps. To demonstrate application of the direct stiffness finite element method, an analysis program developed by JPL called Structural Analysis and Matrix Interpretive System (SAMIS) was used in this study, allowing comparison of vibration data from 10 to 300 cps. The Saturn V model was also tested by itself on a two-cable mount system in a study of its free-free lateral vibration characteristics (ref. 20). In this study, a transfer matrix approach was used to model the system analytically and demonstrated the importance of including shear deformation in the predictions. Differences of up to 32% in the 1st bending mode were reported between the analysis and test due to errors in the tie-down constraints. A summary of advances in structural dynamics resulting from the Saturn program was presented in Ref. 21.

1/15 scale Shuttle dynamic model (1971)-A 1/15-scale dynamic model of an early shuttle tested at Langley.The model was also intended to serve as a source of early parametric data to be used to evaluate analytical procedures for component mode synthesis and to develop test and analysis methods for more complex future models. The model was essentially a stick-type model constructed from tubular-type beams joined together by two spring assemblies, the stiffness of which could be varied to represent a range of interface attachment conditions A two-cable suspension system was employed to support the model and to simulate flight conditions. A summary of the experimental and analytical studies conducted using the model may be found in references 22-26. Advanced substructuring techniques were developed to handle structures too large to be solved by direct methods. Also developed was a vibration data analysis program (VIDAP) to study mass and stiffness uncertainties. The first five modes appeared under 6 cps with the error between test and analysis of about 12%.

Shuttle 1/8-scale dynamic model (1975)- To assess the adequacy of analytical modeling procedures and to provide the test data with which to understand the dynamic behavior of shuttle-like configurations, a 1/8-scale dynamic model of an early shuttle four-body concept was built for structural dynamic studies at Langley. The model was intended to provide early confirmation of analytical modeling procedures, to gain understanding of the dynamics of shuttle-like configurations, and to identify any previously unanticipated dynamics problems. Because the design of the shuttle was preliminary at the time of its construction, replication of the structure was not warranted. Although the model built did incorporate substantial structural detail, simplifications were made in many areas and the model was designed to be only dynamically similar to the full-scale design at that time. Comprehensive static and dynamic tests and analyses were performed on the vehicle in the fully mated configuration shown in Fig. 3 as well as in several partially mated configurations. Detailed descriptions of various aspects of the design, construction, testing, and analysis of the 1/8-scale Space Shuttle model may be found in references 27-36. Noteworthy are two efforts reported in Ref. 36: first is the use of a 2500 degrees-of-freedom of NASA structural analysis NASTRAN model to conduct the vibration analysis of the 1/8 scale shuttle model, and second was the application of the Fast Fourier Transform (FFT) to analyze vibration data. The rather large (for its time) NASTRAN model was reported to use 2 ½ hours on a CDC 6600 computer to obtain the 1st symmetric and 1st anti-symmetric modes. On the testing side, results from conventional sine-dwell testing were compared to results obtained using random inputs and FFT analysis. Although the FTT approach was considered a secondary approach for verification purposes, it proved to provide comparable results to the well established sine-dwell technique.

Langley Structural Dynamics Research (1980-2000)

One of functions of the Structural Dynamics Branch at Langley Research Center is to conduct basic research and focused technology studies on the dynamics and control of flexible spacecraft. This work includes the development of analysis and prediction methods for application to such spacecraft as the International Space Station, earth-observing science platforms, and solar system exploration spacecraft. The methods developed are verified and improved through experiments on research hardware. In the mid-eighties significant emphasis was placed on interdisciplinary experiments on the control of flexible spacecraft, the use of scale models for spacecraft development, and advanced algorithms for system identification. The focused technology activities constituted the largest part of the Branch's work and were divided into two general but complementary categories: Dynamics Verification Technology (DVT) (Refs. 37-38) and the Controls-Structures Interaction (CSI) (Refs. 39-40). DVT had the objective of developing and validating ground test and analysis methods based on the use of scale models for predicting and verifying the on-orbit dynamic characteristics of large and/or flexible spacecraft structures which cannot be ground tested at a high level of assembly or operational realism. The International Space Station was selected as the focus structure for this program because it would be the first such structure constructed in space, it is a real structure which is typical of the structures of interest, and it would provide the first opportunity to obtain full-scale ground and flight data for correlation with data obtained from scale models. The approach adopted involves a test and analysis program utilizing a series of models with increasing structural and dynamic complexity, culminating in a near-replica model of the space station. The replica model would then serve as a dynamics test-bed for examining any on-orbit dynamics problems which might arise for the station and to perform basic research on the structural dynamics of spacecraft structures.

Generic Multi-Body Dynamic Model (1986)- When the scale models program was initiated, a number of structural designs were under consideration for the space station and a reference configuration had not yet been selected. However, common features of the designs were the use of cylindrical modules for habitation and laboratory facilities, solar array panels for power generation, and radiator panels for heat dissipation. These components were interconnected as shown in Fig. 5 to form an integral orbiting station . For this reason, the first model in the planned series of models was a generic, multi-body, dynamic model intended to simply exhibit the type of low-frequency behavior which was expected to be characteristic of the stations being considered, and to serve as a basis for developing test and analysis methods for such structures. The model consisted of a cylindrical habitation module, two flexible solar array panels, and a radiator panel, all attached to a stiff connecting cube by band clamps. The model was 30-ft long and 12-ft high. Although no scale factor could be chosen in the absence of a full-scale design, the model was designed so that it had system natural frequencies which were in the range of those that a 1/10-scale dynamic model might be expected to have (less than 1 Hz). Ground vibration tests of the model were performed with the model suspended from 2 cables in the Langley 55-ft vacuum chamber in a manner to simulate free-free boundary conditions. Tests were performed both in air and vacuum (9mm Hg). Modal vibration tests were conducted on each substructure as well as the assemblage to provide data for component mode synthesis studies. Data from servo accelerometers were used to measure responses and impact hammers and electrodynamic shakers were used as excitation sources. A Hewlett Packard 5451C computer system was used to acquire the data and to compute curve fits from the frequency response functions to extract the modal parameters. The Engineering Analysis Language (EAL) finite element program was used to predict the vibration modes with a total of 3700 degrees-of-freedom. The simulated solar array models frequency error, when updated using static test data, was reduced by an average of 8.1% to 2.8%. Damping levels were shown to be significantly impacted by the presence of air. An average increase of 29% was exhibited when ambient air was present. A detailed description of the model and a discussion of the tests conducted and the analyses performed are given in references 41-42.

Early Space-station 1/10-Scale Generic Model (1988)- In the early stage of the station design, it was apparent that the station would employ an erectable-truss structure to which would be attached modules, solar arrays, radiators, and equipment pallets (see figure). For this reason, a 1/10-size generic model was built by Lockheed to be functionally similar to that being proposed for the space station at that time and to simulate the dynamics of the structure. The generic model was made from commercially available aluminum truss structure hardware known as Meroform. Each bay was a cube 0.5-m on a side and weighed approximately 7 lbs. Although the joints and struts were not scaled, when assembled and mass loaded, the model provided a good 1/10-scale dynamics simulator. This model was a precursor to a hybrid-scale space station model. The reader is referred to references 43-46 for a more complete description of the tests and analyses conducted with this model.

Early Space Station Hybrid-Scale Dynamic Model (1988)- With the completion of the erectable space station design shown previously, design was started on a dynamically-similar model of the station (ref. 45) which was intended to be used to develop test techniques and suspension methods for the testing of the replica model which was to follow. The new model was designed to exhibit the dynamic behavior of a 1/5-scale replica model but to be 1/10-scale in overall dimensions (see Fig. 6) . One-tenth scale bay size was dictated by availability of existing test facilities at Langley. The one-fifth dynamic scale factor was dictated by fabrication limitations in the manufacturing of the joints. The model had the same overall size as the 1/10-scale generic meroform truss model. The convention used to describe the model is 1/5:1/10-scale. Hybrid scaling laws were developed (refs. 45-46) and validated. The model consisted of ten bays of truss, rotary alpha and beta joints, various pallets, and rigid and flexible versions of solar arrays and radiators. Static and dynamic tests of each component were performed with boundary conditions that approximated those which the component had in the integrated system. Shown in the photograph was the Mission Built (MB) configuration number five. The finite element model (FEM) of each component was modified based on the results of the test-data analysis and used to form an updated system model. A detailed description of correlation analysis conducted on this model was reported in Ref. 47. Reported frequency errors for the updated model was less than 5% with cross orthogonality values greater than 90%. This was an improvement of over 50% for some modes. Hybrid scaling proved to be accurate to within 1% in the range of interest. Frequency improvements for certain modes was as high as 20% for six modes in the analysis range. Also improved were results from cross orthogonality of the generalize mass matrix, which went from 60% to over 90% in some modes. Test Analysis Models (TAM) provided an excellent tool to evaluate and correlate FEM models with test data, to study various model reduction techniques, and to select sensor locations.

Advanced suspension systems (1989)- The issue of how to design and evaluate suspension systems to reduce the effects of the suspension on the dynamics of the test article had been the subject of research for years (Refs. 48-62). As part of the DVT research program, a technique for suspending such structures in a manner which simulates unrestrained, on-orbit conditions was developed and evaluated. The concept involves hanging the structure by a set of cables, the upper ends of which are connected to devices which support its weight with modest static deflection, yet offer near-zero vertical stiffness for small motions from this deflected position. The low compliance required for motions in the plane parallel to the ground is achieved by selecting a cable length, that yields pendulum frequencies sufficiently lower than the frequency of the lowest flexible mode. Two types of devices have been studied (refs. 54 and 57). One is an all-mechanical, passive device called the zero-spring-rate-mechanism (ZSRM), and the other is a hybrid pneumatic/electromagnetic active device termed a P/ESD. The ZSRM is based on the use of a combination of springs and levers arranged to operate in a manner that provides the desired low level of stiffness for small motions from equilibrium. The idea on which the device is based is not new (refs. 58-59) and there are several early applications, that have been reported (for example, ref. 60). Current versions of these devices employ state-of-the-art technology for improved capability as well as performance (refs. 54 and 57). Active pneumatic versions of the device appear to be of more recent origin. Both types of devices are described more fully in references 54 and 57. Some key findings showed that mass coupling of the test article with the suspension system will lower the resonant frequencies, but stiffness coupling will raise them. For the test article shown in Fig. 7, mass coupling dominated and resulted in a net decrease in the frequencies. The ZSRM produced extraneous modes that in some cases could interfere with the test results. Since the test article was lightly damped, both suspension systems added significant damping to the data. Overall, results obtained using the advanced suspension system were substantially better than those obtained using conventional suspension methods.

Damage Detection (1989)- As part of the DVT program, the development and evaluation of methods for damage detection in flexible truss-type structures using modal data was undertaken. Early efforts, employing a ten-bay meroform generic truss, were described in references 63 and 64. More extensive studies were conducted on the eight-bay cantilevered truss shown Fig. 8. A comprehensive experimental investigation was conducted concurrently with the development of a new analytical method for damage detection based on an innovative application of the eigenstructure assignment method used in designing control systems (refs. 65-68). Modes and frequencies for 16 damage cases were obtained for the truss. The damage cases included single members removed, multiple members removed, and partial damage to a single member. Three accelerometers at each node (for a total of 96) provided complete mode shape definition for the structure. Results obtained from this study indicated that damage detection with real data is difficult. The ability to locate damage depends strongly on the number of sensors as well as on measurement and modeling accuracy. Further, the damage must impact the modal properties at levels that exceed the levels of uncertainty that arise from modeling or testing. A detailed discussion of modal data issues associated with damage detection is given in reference 67. A complete summary of the ground vibration tests conducted as part of this study is contained in reference 68. The large quantity of high-quality test data constitutes a unique database for damage detection work and is currently being used by other researchers to validate system identification techniques and damage detection/location methods.

Hoop column antenna (1986)- A number of large space antennas were proposed for communications and remote sensing missions during this time period. A 15-meter diameter proof-of-concept scale model based on a 100-meter point design was constructed for deployment, electromagnetic, and structural testing. The concept was referred to as a hoop-column antenna. It employed a deployable structure composed of a hoop around an axial telescoping column that was stiffened by cables from the column ends to the hoop. The antenna mesh was attached to an outer compression ring or hoop. As part of the test program, static and dynamic tests were conducted in the Langley 16-meter Vacuum Chamber (Ref. 69-71). The model, was mounted on a tripod support structure and accelerometers were placed on the hoop to measure the hoop acceleration due to inputs from a non-contacting electromagnetic shaker placed on the hoop. Because of difficulties getting to the membrane surface, no dynamic measurements were obtained for the mesh itself. Good agreement between analysis and test data was obtained, but only after the finite-element model was refined using static test data.

Mini-Mast (1991)- This structure, shown partially deployed inFig. 9, was an 18-bay, 20-meter-long, deployable, flight-quality truss (refs. 72-74) intended to demonstrate the deployment mechanism of a proposed flight mast under the Control of Flexible Structures (COFS) flight experiment. Unfortunately, COFS was terminated before reaching flight but hardware developed for it, such as the Mini-Mast, was extensively used. The objective was to conduct comprehensive active vibration control experiments on a realistic large space structure. The mast, which was 1/3 of the length of the Mast considered for COFS, was constructed of three longerons having a triangular cross-section 1.2-m on a side and made of graphite/epoxy tubes. The truss has characteristics associated with future space structures, namely, low frequencies, closely-spaced modes, and joints, which introduce nonlinearities into the truss dynamics. This structure exhibited clustering of modes near dominant bending modes, due to massive joints placed in the middle of diagonal truss elements, resulting in a total of 108 additional models in the frequency range from 15 to 20 cps (Refs. 75-76). It was deployed vertically inside a high-bay tower, cantilevered from its base on a rigid foundation. Actuators and sensors for control were located on two stiff platforms at the tip and near the mid-point of the truss. Actuators consisted of torque wheels and proof-mass actuators. The combined mass of the actuators exceeded the total truss mass and had to be off-loaded using a cable. Non-contacting displacement transducers were used as sensors to provide feedback signals for control and to conduct modal surveys. An input/output interface converted signals to and from the structure into signals that were manipulated in a Cyber 175 main-frame computer for control action. Additional data for system identification was also collected using various commercially available spectrum analyzers and analyzed using the Eigensystem Realization Algorithm (ERA) (Ref. 77) and Polyreference. Work on the Mini-Mast was perhaps the first instance where system identification was conducted at Langley not only for the purpose of determining modal frequencies, mode shapes, and damping values of a flexible structures, but also to identify transfer functions between the control actuators and sensors. This fostered a new class of identification tools (Ref. 78). Mini-Mast was used extensively by CSI guest investigators to verify candidate control laws for vibration control (Ref. 72). Lessons learned from this activity highlighted the need to integrate system identification with control experiments since even the most robust control design strategies proved to be unstable under certain test conditions.

Phase 0 evolutionary model (1991)- was the second test article for CSI testing at Langley. The concept of this model was that it would evolve over time in size, complexity, and experimental capabilities. The Phase-0 CSI evolutionary model (CEM), shown inFig. 10, was designed and built for studies related to line-of-sight pointing control. The aluminum model had five major structural components: a 16.8-m, four-longeron center truss, an eight-rib reflector 4.9-m in diameter, a 2.8-m tower, and two 5.1-m cross-member trusses (ref. 79). It was suspended by two cables 19.8-m long attached to two pneumatic low stiffness devices fabricated by CSA Engineering. The structure was designed to have the dynamic characteristics typical of spacecraft platforms proposed for remote sensing and communications. Sixteen air thruster actuators were distributed on the structure along with eight accelerometers and eight angular rate sensors for feedback control. In addition, a laser-detection system was incorporated into the test-bed. A laser beam, whose source is located at the top of the tower, is reflected off a mirror, that is located at the center of the reflector onto a detector mounted on the ceiling of the lab. This detector signal was used as the performance metric for most control experiments. To study various control computer architectures, a customized Computer Automated Measurement and Control (CAMAC) system was assembled with several independent modules to operate and control different parts of the experiment. Data from the testbed were digitized and fed into a centralized computer system used for data collection and to implement centralized/decentralized closed-loop experiments. Comparison of test and analysis showed agreement of the first 3 flexible modes within 5%, but higher frequency modes above 10 cps were not predicted as well. Nonlinear suspension effects due to hose attachments to the model produced damping values from 0.6 to 4.7% in the suspension modes. A synopsis of test results and knowledge gained with this model is documented in Ref. 80. Among the lessons learned in this investigation are the need to conduct component tests for incremental/systematic updates of the finite element model, truss joints fabricated to carry 1600 lbs. loads produced 0.1 to 0.3% critical damping in the flexible body modes, servo accelerometers can be used for feedback control of low (0.15 cps) frequency dynamics, and model based controllers are usually more energy efficient than dissipative controllers for the same performance level.

Phase 1 evolutionary model (1992)- The Phase-I model looked similar to the one shown in the photograph, from a distance, but the structure was completely redesigned and fabricated according to results from an optimization-based integrated control/structure design tools (Refs. 81-83). Design and fabrication of the testbed was contracted to Lockheed Missiles and Space Company (Ref. 84). The instrumentation and control computer were identical to those used with the Phase 0 model. Work on Phase I demonstrated experimentally, for the first time, that by including both controls and structures requirements in the design of the structure one can reduce power consumption by 60% while maintaining the same line-of-sight performance level and structural weight. Since the total structural weight was not allowed to change, the optimization solution re-distributed the structural stiffness to modes that affected the control performance, specifically, the second, third and fourth bending modes. Also demonstrated was methodology to include mass and stiffness constraints from optimization tools into a realistic truss structure designed to realize the full benefits of the optimized design. This particular version of the structure had a very short life and was quickly reconfigured to a Phase II configuration.

Phase II evolutionary model (1993)- This configuration was supported from four cables connected to an actively controlled suspension system (Ref. 85). The 4-cable suspension system reduced the corruption of acceleration data from the gravity field during rigid body pendulum motion. Also featured in this model were three science instrument simulators (SIS) comprised of two-axis gimbals with companion laser and optical scoring systems to simulate science instruments on a spacecraft. Using a laser source mounted on the structure and pointed towards an optical scoring system on the ground, a scientific payloads on a spacecraft can be simulated. The optical scoring system measured incident angles of the incoming laser beam with respect to ground with a field of view of 1000 arc-sec. The CAMAC system was used with several independent modules to operate and control different parts of the experiment. For example, each gimbal was commanded with independent scanning profiles while controlling the system with thruster actuators. This allowed for centralized and decentralized control schemes to be demonstrated with the same test configuration. The structural test system was based on a ZONIC system 7000 DAS. This system provided for simultaneous data acquisition of 256 channels and 8 channels of command signals to the actuators. Because the model was suspended from cables and was free to move, only the control actuators were used in the modal test. Test results correlated well with analysis for the first 20 flexible modes in the 0 to 30 cps range. This structure served as a testbed facility for guest investigators. In particular, Martin Marietta conducted a study combining passive methods, using 60 struts with viscoelastic material, and active controls to demonstrate attenuation levels from 10 to 20 db. One unique aspect of this was the analytical design of damping levels for various structural modes, which were later confirmed during testing. Although the testbed prove to be useful for various technology demonstrations, to satisfy a more immediate need to work with structures closer to a real spacecraft configuration, the Phase II model was once more reconfigured to a Phase III configuration resembling the bus structure of the Earth Observing Satellite.

Phase III Evolutionary model (1993)- This reconfiguration occurred in response to the need to develop and test CSI technologies associated with typical planned earth science and remote sensing platforms such as the Earth Observing Platform, the Defense Meteorological Satellite Program (DMSP), LANDSAT, and many others. The EOS AM-1 configuration was selected as the target system in the reconfiguration study conducted by Lockheed (Ref. 86). The EOS AM-1 dynamics testbed, shown in Fig. 11, provided a ground test capability to study system level pointing performance of multi-payload spacecraft. The testbed was a major advance in ground test capability for the measurement of vibrational jitter and for the development and validation of vibration control, payload isolation, and disturbance rejection technologies. Three scanning payloads (two-axis gimbals) were attached to a primary bus structure for simulation of remote sensing missions. The primary structure is a modular aluminum truss that has been configured in the full scale geometry of the EOS AM-1 spacecraft with a 1/10 inertia scaling. This scaling results in the testbed frequencies of vibration to be quite near the EOS AM-1 spacecraft vibration frequencies (~23 cps for the first bus mode). The truss was supported by a pneumatic suspension system to mitigate gravity influences on the testbed dynamics. All six rigid body modes had frequencies less than 0.2 cps. Various control systems were implemented using both inertial and embedded actuators in conjunction with a number of sensor units. The payloads (gimbals) simulate the class of instruments typically used by the EOS series of satellites. The payloads can scan +/- 7.5 degrees with an accuracy of less than 2 arc-seconds. A specially designed scoring system was employed to measure the inertial pointing angle of each payload. This scoring system had a range of +/- 500 arc-seconds with a resolution of less than 0.15 arc-seconds. To obtain this dynamic range, all communication to and from the payloads is digital. Simultaneous measurement of 200 channels of data can be recorded to assess the dynamic response resulting from either external or on-board disturbances. Computer simulation of control and structure interaction required the development of very efficient tools to couple the control actions with the structural responses. Simulation models with one thousand states were not usual and required efficient analysis codes. A code known as PLATSIM was developed for that purpose (Ref. 87). This multi-payload testbed had been used to test a number of jitter reduction technologies. Two noteworthy demonstrations conducted on the testbed were: a vibration attenuation module built by Harris Corp., capable of payload isolations of 40 db, and the second demonstration was a cryocooler harmonic disturbance rejection of 40 db conducted by GSFC.

FLIGHT EXPERIMENTS

Long Duration Exposure Facility (LDEF) (1980)- LDEF, shown in Fig. 12, was an orbiting spacecraft of passive scientific experiments released from the Shuttle to study exposure to space environment issues. Experiments were contained in rectangular and square trays distributed over the structural framework (72 trays distributed over the cylindrical surface and 14 on the end bulkheads). Because it was planned to be the first shuttle payload (at the time), LDEF was subjected to extensive static and vibration tests. Of fundamental importance was the effect of the experiment trays on the overall dynamic behavior of the payload. Finite element modeling was performed using the SPAR program (Refs. 88-89). Since the investigation was focused on the low frequency vibration modes, the analysis was developed to be valid up to a frequency of 50 cps. A fundamental problem in the analysis was the representation of the tray dynamics particularly the complex stiffness due to tray offsets from the neutral plane of the structural framework. Simplified analysis without the offsets resulted in overall frequencies significantly different from tests. In the final tray analysis, the tray stiffness was represented as an equivalent orthotropic panel with coupled extensional-bending and shear twist stiffness. Dynamic testing was conducted to certify the payload for flight, which required that the fundamental mode be greater than a pre-specified shuttle requirement. LDEF was tested on air bags supporting the structure at the Shuttle interface support points. Multiple shakers, mounted from cables with in-line springs, were used to excite the structure using random inputs and data from accelerometers were used tomeasure responses. Data analysis was conducted using an HP 5451C computer system. During the initial test, local vibrations of the trays dominated the responses to the point where they had to be removed for a frame-only test. Tray response nonlinearities was one of the biggest problem during correlation of the data. Correlation errors for the 1st lateral bending mode went from 2% to 4% when the trays were included.

Solar Array Flight Experiment (SAFE) 1984- On August 1984, the OAST-1 Solar Array Experiment was deployed from the Shuttle (see Fig. 13). It was fabricated by Lockheed Missiles and Space Flight Company from 3-mil thick Kapton and consisted of 84 panels, each 15 inches wide by 13 ft long, joined edge to edge to form a 105 foot tall array. For launch and reentry, the array had to be folded accordion like into a 3 inch thick stack. Deployment was accomplished using a triangular-shaped coilable mast. NASA Langley participation in the flight experiment managed by Marshall Space Flight Center (MSFC) was to study the structural and control dynamics of a new class of large lightweight, low frequency space structures, and to develop technology for remote video measurement of structural motion (Refs. 90-92). The shuttle orbiter closed circuit television (CCTV) was used to provide recorded video images of the solar array from four locations in the payload bay. White reflective targets were placed on the array to provide discrete points at which to track the array motion. A dynamic test consisted of a quiescent period in which crew and orbiter operations were restricted, followed by an excitation period using the vernier reaction control jets on the Shuttle, and a free-decay period. By tailoring the thruster firings, different modes of the structure were excited. Analysis of the flight data was done on the ground and required three major steps: each video tape is analyzed to determine motions of target in the camera image plane, triangulation of four camera images to determine 3-D motion in the orbiter coordinate system, and the last step was to process the data using system identification algorithms. Two algorithms were used in the data analysis, the standard FFT analysis and the ERA system identification program. During the experiment, difficulties were reported when using natural lighting because extraneous reflections occurred and in some cases obscured the targets.

Photogrammetric Appendage Structural Dynamics Experiment (1995)- PASDE was designed, developed, and flown to demonstrate the use of photogrammetry to the measurement of the vibration response of the Russian Space Station Mir Solar array, shown in Fig. 14 (Ref. 93). In contrast to the SAFE flight experiment, this experiment used natural scenes features without a priori placement of targets in the determination of the solar array motion. Six video cameras and recorders were placed in canisters in the Space Shuttle cargo bay to record images of the root and tip of the solar array. Video images, processed on the ground, had to be digitized, correlated to a particular tractable feature on the image, triangulated from multiple cameras to recover displacement information, and then processed by the system identification algorithm. Identification results showed three solar array bending modes and two system modes involving the Shuttle and Mir Space Station. The three solar array bending modes identified had frequencies under 0.5 cps with damping levels under 4.4 %.

Testbeds for vibroacoustic research (1999)- Two fuselage structures an "aluminum testbed cylinder" (ATC) and a Beechcraft Starship fuselage were tested at Langley to develop test-verified finite element models (Refs. 94-97). The finite element models, as well as the physical structures themselves, will serve as research testbeds for a variety of interior noise reduction studies. NASTRAN finite element models of both structures are being developed and validated by conducting modal tests. The photograph in Fig. 15 shows the structures located in the Structural Dynamics Laboratory. Each structure was mounted on soft supports to simulate free-free boundary conditions: the ATC uses bungee cord at each end and the heavier Starship fuselage uses four air bags. Each modal test has up to 300 accelerometers and 4 to 7 shakers operating simultaneously. Test results consist of natural frequencies, damping factors, and mode shapes of all modes of vibration up to a frequency of at least 250 cps. For the Starship, the biggest problem was to determine the composition of the composite lay-up for the different sections of the fuselage. Finite element models have been developed for both structures. The geometry of the ATC model was obtained from engineering drawings, whereas the geometry of the Starship fuselage required a photogrammetric survey because engineering drawings were unavailable. Figure 15 shows both structures in their initial test configurations. To date, approximately 100 modes of the ATC (up to 250 cps) and 40 modes of the Starship (up to 150 cps) have been identified experimentally using ERA. The ATC and Starship fuselage testbeds provide test-verified structural dynamic models to evaluate and refine various competing noise-reduction technologies including both passive and active damping techniques. Noise prediction tools often require high frequency modal information not collected under traditional structural dynamics tests. This high frequency regime is fostering the use of broad area measurement devices such as laser vibrometers or photogrammetric techniques to examine localized behavior of components driving the noise propagation problem.

System Identification Algorithm Development- One of the most significant advances in the area of dynamic testing in the eighties, was in the system identification algorithms area. Although the Fast Fourier Algorithm (FFT) was published in the mid sixties, computer systems that could take advantage of the FFT technique were not readily available until the seventies. With the availability of computer systems, modal testing using sine dwell excitation diminished in favor of a faster testing approach using random excitation and FFT. To extract modal parameters, techniques for curve fitting data in the frequency domain was part of practically every spectrum analyzer sold. These techniques worked well on most cases that did not exhibit closely spaced modes. Time domain approaches have always been used in the analysis of data, but in the late seventies they started to be used as an alternative to the now established frequency domain curve-fitting approaches to analyze the most difficult identification problems (Refs. 102-103). The control community, from the development of the Kalman filter in the sixties, has recognized realization theory as a mathematical tool to recover models from input/output data. Taking advantage of the work conducted by Kalman and co-workers, in the early eighties, the Eigensystem Realization Algorithm was developed at Langley (Ref. 77) in 1984 for modal parameter identification and model reduction of dynamic systems using pulse response data. The first application was the Galileo modal testing using 162 accelerometers distributed over the test article and several shakers. In 1990, a method was developed to compute pulse response of a linear system, from which the state-space model and a corresponding observer were determined simultaneously. With the increase emphasis on controls of flexible structures in the nineties, algorithms that provided models directly usable for controls gave rise to two new developments, the Observer/Kalman Filter Identification Algorithm (OKID) (Ref. 78) and later the Observer Controller Identification Algorithm (OCID)(Ref. 98-99). The method was used to analyze the closed-loop response data for the Hubble Spacecraft Telescope excited by the solar panel vibration and to identify the flutter modes of an aircraft model tested in a wind tunnel. Script computer programs written using the commercially available MATLAB software was used to develop and distribute the algorithm. The next class of algorithms being developed is autonomous adaptive identification algorithms. Two different goals are being pursued with this work; one is to automate the data analysis process to minimize human intervention, and the second goal is to realize models and controllers on-line to adaptively controls systems (Ref. 100). Both on them have been successfully demonstrated in laboratory tests.

Autonomous Modal Identification Algorithm Research Objective (1998)- The objective of this work is to create an autonomous version of the popular Eigensystem Realization Algorithm (ERA) for in-space identification of the modal parameters of spacecraft during their lifetime. The structure used for demonstration was the Resource Node, the first U.S.-built component of the International Space Station (Ref. 101). The modal test was conducted by the NASA MSFC in January 1997 using an exceptionally high number of accelerometers (1236). With commercially available software, the test team identified 45 modes of vibration from 0 to 50 cps. Prior to receiving the MSFC report containing their test results, an independent modal analysis of the same set of frequency response functions (FRFs) was performed at Langley using the autonomous ERA software. The ERA analysis used all 3708 FRFs simultaneously (3 shakers x 1236 accelerometers), with each FRF having 1600 lines of resolution. The autonomous ERA calculations required a few hours of CPU time on a UNIX workstation, compared with several days of iterative data analysis performed by the test team. There was excellent correlation of mode shapes between the MSFC and ERA results for the first 21 vibration modes of the structure up to 35 cps. From 35 to 50 cps, about 60 percent of 25 additional modes had excellent correlation. Natural frequencies and damping factors of most modes agreed within 0.1 cps and 0.2 percent, respectively. Figure 17 shows a typical FRF and identified mode shape. These results demonstrate the feasibility of autonomous structural modal identification using ERA. More experience is necessary to increase reliability of the autonomous procedure.

CONCLUDING REMARKS

This paper has presented NASA Langley's history on dynamic testing and related analysis development in the past four decades from the Structural Dynamics Branch viewpoint. Scale models have played a significant role in addressing key dynamic issues associated with almost every major launch vehicle ever considered but not as much in spacecraft design. Langley has contributed to a broad range of experimental and analytical studies, which advanced the technology base needed for designing and building spacecraft structures. In particular, the studies have contributed substantially to increase understanding of the many unique dynamic characteristics of spacecraft and in the resolution of anomalies when they have occurred. Test methodologies have seen a significant improvement as technology in terms of sensors, actuators, computers, and particularly algorithms have significantly reduced the amount of time required for test and analysis. The numerous lessons learned from the different activities represent a wealth of information for anyone involved in dynamic testing and analysis.

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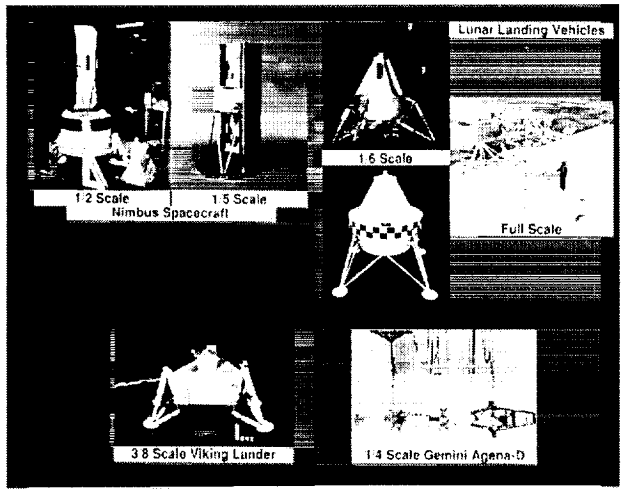


Fig.1 Early spacecraft models

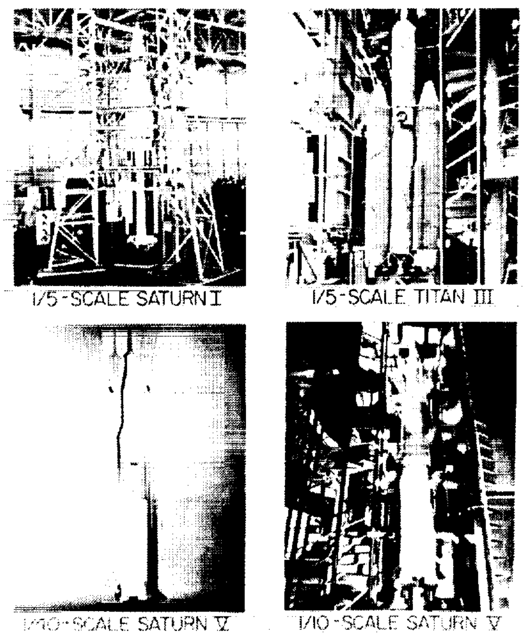


Fig. 2 Launch vehicle scale models

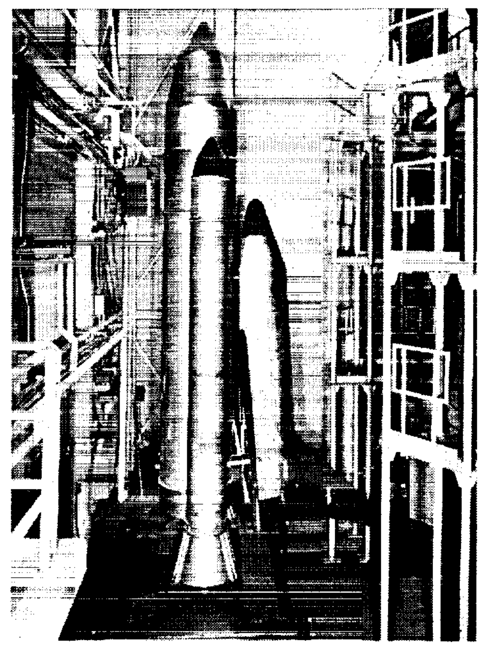


Fig. 3 Space Shuttle 1/8 scale model

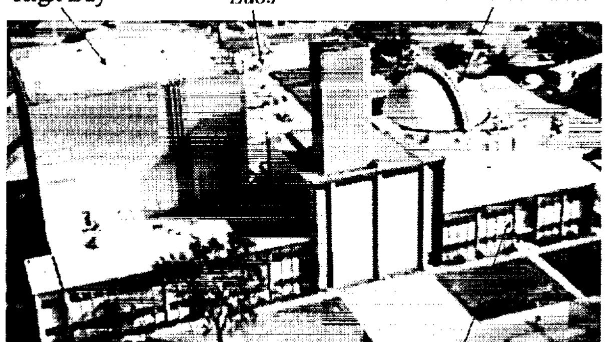


Fig. 4 Structural dynamics Complex

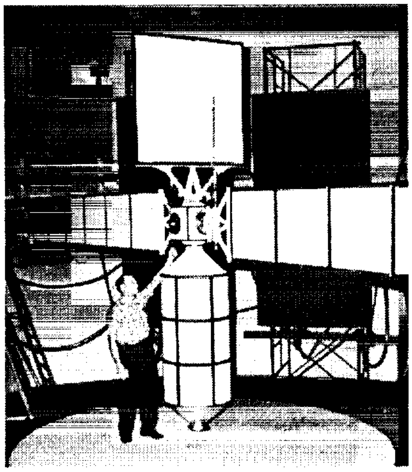


Fig. 5 Generic multi-body dynamic model

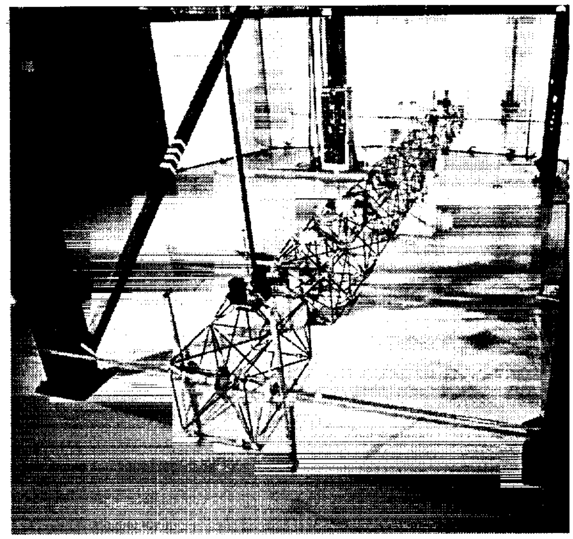


Fig. 6 Hybrid-scale space station model (early configuration)

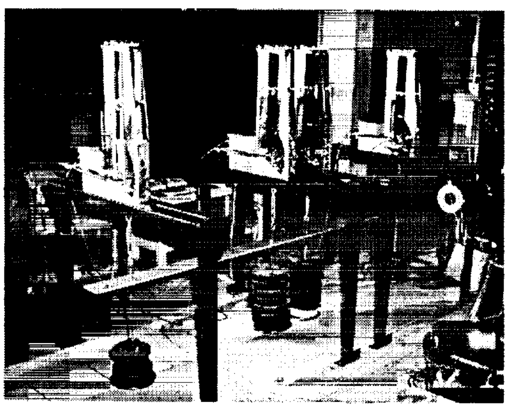


Fig. 7 Advanced suspension system

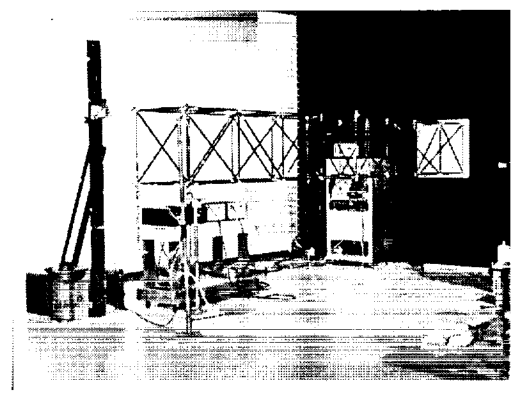


Fig. 8 Damage detection experiment

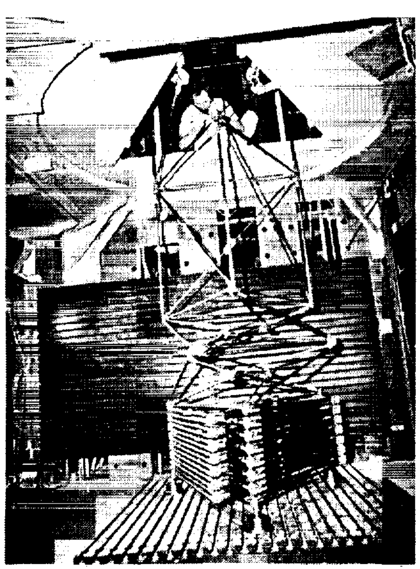


Fig. 9 Mini-Mast structure

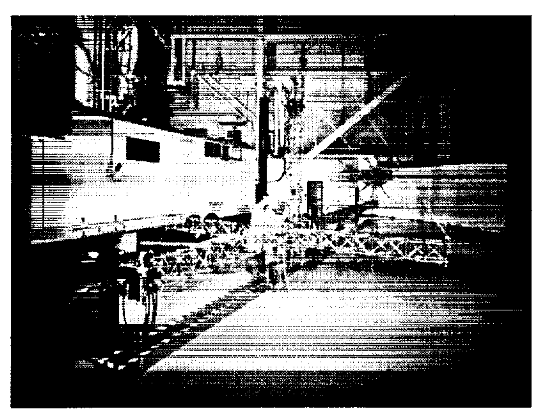


Fig. 10 Control Structures Interaction: Phase 0 model

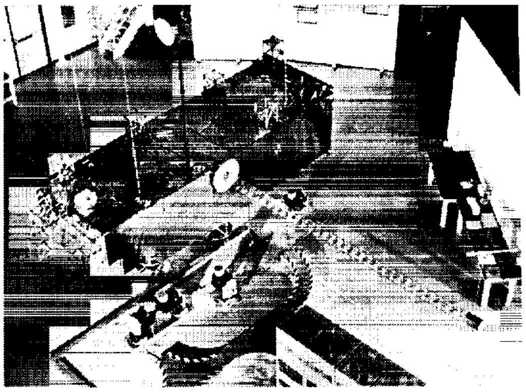


Fig. 11 Control Structures Interaction: Phase III

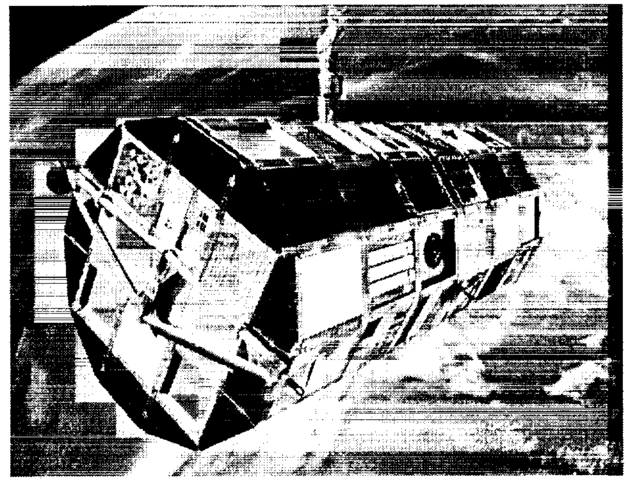


Fig. 12 Long Duration Exposure Facility (LDEF)

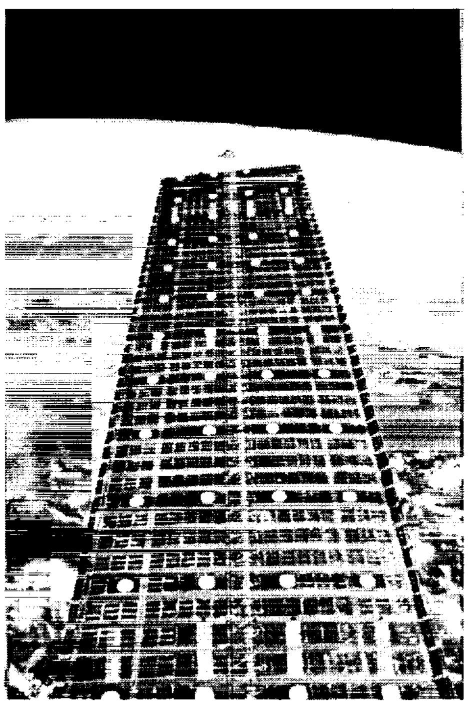


Fig. 13 Flight Experiment Solar Array Flight Experiment (SAFE)

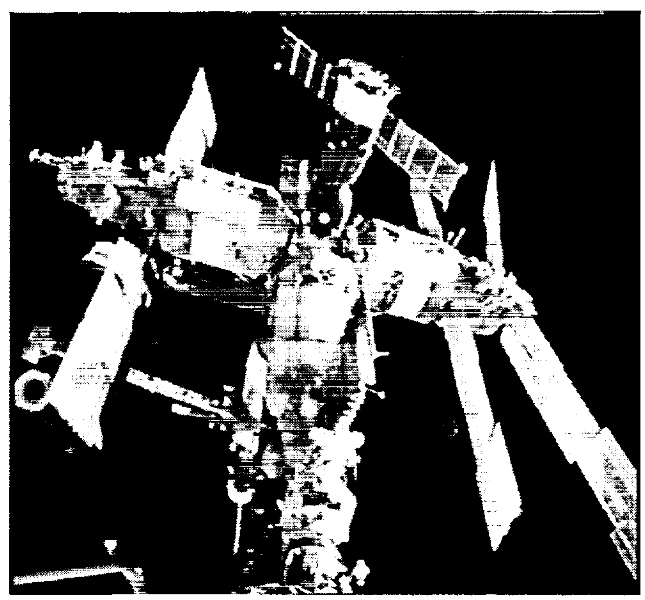


Fig. 14 Photogrammetric appendage structural dynamics experiment

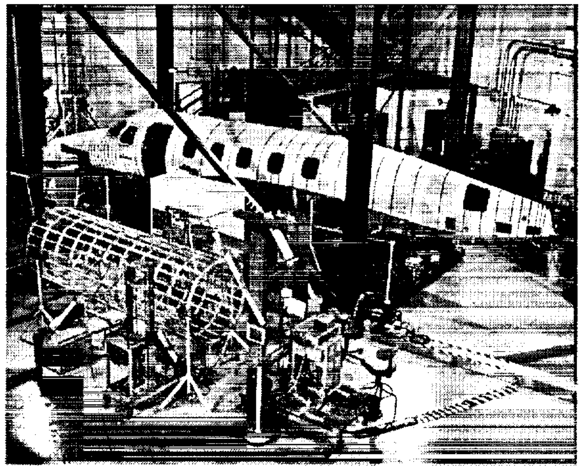


Fig. 15 Testbeds for vibroacoustic research

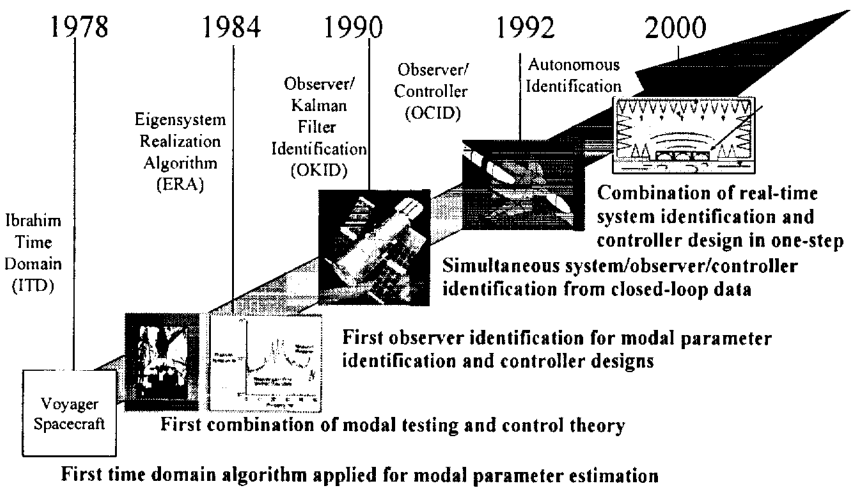
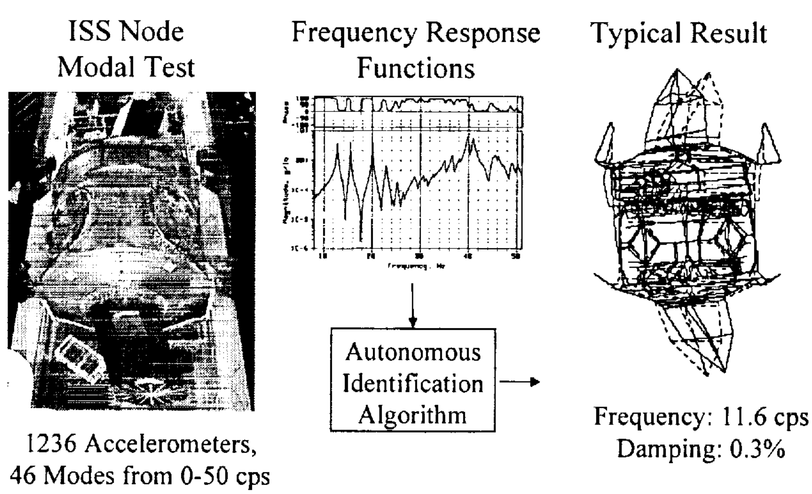


Fig. 16 System identification algorithm development



• Analysis time reduced from several days to approx. 7 hrs

Fig. 17 Autonomous modal identification